Increased High-Temperature IC Packaging Reliability Using Die Extraction and Additive Manufacturing Assembly

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Abstract

Semiconductor parts are most often specified for use in the “commercial” 0 to 70°C and, to a lesser extent, in the “industrial” -40 to 85°C operating temperature range. These operating temperature ratings generally satisfy the demands of the dominant semiconductor customers in the computer, telecommunications, and consumer electronic industries. There is also a demand for parts rated beyond the “industrial” temperature range, primarily from the aerospace, military, oil and gas exploration, and automotive industries (-55 to +125C, and even higher). However, the demand has not been large enough to attract or retain the interest of major semiconductor part manufacturers to make these parts. In fact, wide temperature range parts are becoming obsolete and functionally equivalent parts are not replacing them.

Today, for some applications, it is difficult to procure parts that meet engineering, economic, logistical, and technical integration requirements of product manufacturers, and that are rated for an extended temperature range (typically beyond 0 to 70°C). In some applications, the product is available only in the “commercial” temperature range, with commercial packaging. If the product application environment is outside the commercial range, steps must be taken to address this apparent incompatibility. For example, oil exploration and drilling applications require small, advanced communication electronics to work underground at high temperatures where cooling is not possible. This is where uprating comes into play.

Despite the fact that a part can be uprated relative to functional performance at higher than specified temperatures, the original packaging and connectivity may not be reliable with long term exposure to greater than 150C due to Kirkendall voiding and general plastic degradation. However, if the original die with gold wire and aluminum pad bond is extracted from the original plastic commercial package and re-assembled into a new ceramic package body, excellent reliability at temperatures exceeding 200C can be achieved. The original gold/aluminum bond interface can be removed and replaced with an electroless nickel, electroless palladium, immersion gold (ENEPIG) process, or a much more economical, automated process can be used. This process is discussed in the accompanying paper and utilizes additive manufacturing to place an aerosol jet silver deposition over the existing gold ball, interfacing with the remaining exposed aluminum. In this manner, a high-reliability connection system can be achieved which is immune to Kirkendall voiding for the temperature range of interest.

Key words

Kirkendall Voiding, 3D Printing, Die Assembly, Additive Manufacturing, Aerosol Spray Assembly, Die Extraction and Re-Packaging, High-Temperature Integrated Circuits, High Temperature Hardening of Commercial Die

I. Introduction

There are many benefits associated with the ability to extract a silicon die from a plastic package, with the two most common reasons being: 1.) re-manufacturing an otherwise known obsolete die/footprint by locating the die within other available package profiles for extraction to reassemble it into the package footprint of interest, and 2.) the potential for hardening the original product relative to high-temperature interconnect reliability. [1]

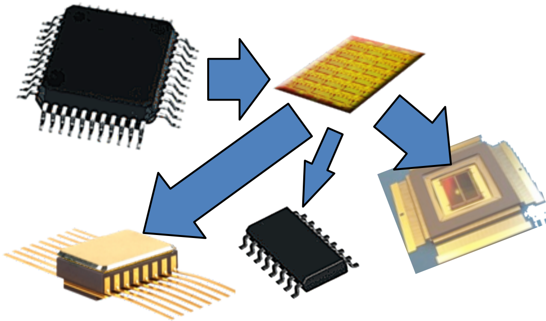


Fig. 1 – Silicon Die Extracted From Original Plastic Package and Re-Assembled Into New Plastic Footprint or Ceramic Package

For high-temperature applications, removal of the original gold ball is necessary to eliminate the overly sensitive gold/aluminum interface which becomes compromised at temperature exposures greater than 150C due to Kirkendall voiding and/or Horsting voiding.[2] It has already been proven that removing the original gold ball, followed by an ENEPIG (Electroless Nickel, Electroless Palladium, Immersion Gold) pad re-plating process dramatically reduces the susceptibility of Kirkendall voiding, even with gold wire reassembly (i.e., no increase in pad interconnection resistance for exposure temperatures of 250C for 2000+ hours).[3]

Additive manufacturing (or 3D printing), with silver aerosol deposition of the new 'bond wires' for subsequent reassembly, has proven to solve both potential issues by overlapping the conductive spray with the still-exposed portion of the aluminum bond pad. In most cases, the remaining exposed aluminum area is actually larger than the contact area for the original bond (see Figure 2).

Assuming a typical square bond pad of 100 um x 100 um, a 1 mil gold wire is formed to a 75 um circular footprint. Therefore the original bond interfaces to a pad area of 4500 um^2 and the remaining exposed aluminum area is 5500 um^2. Given that this is the case, then subsequent silver overspray can be equal to or greater than the original electrical connection interface.

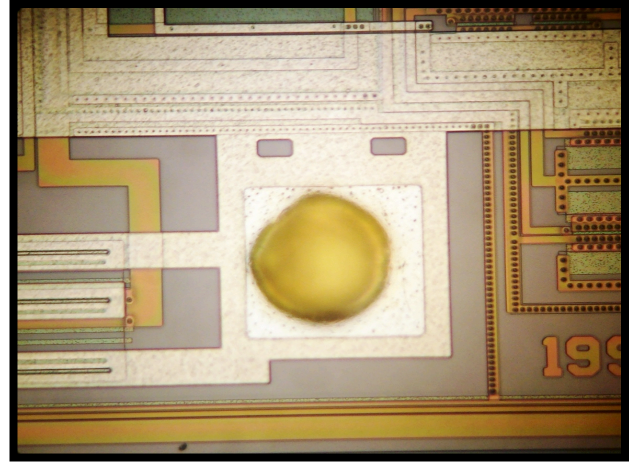
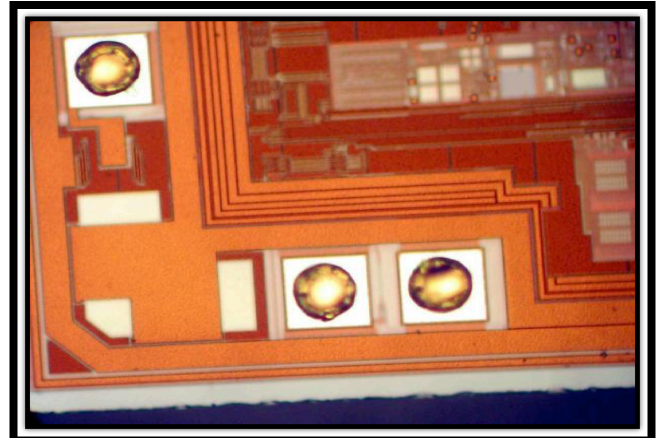


Fig. 2a (above) **and 2b** (below) – Silicon Die Extracted. Note Remaining Exposed Aluminum Area Typical for a Previoiusly Bonded Pad.



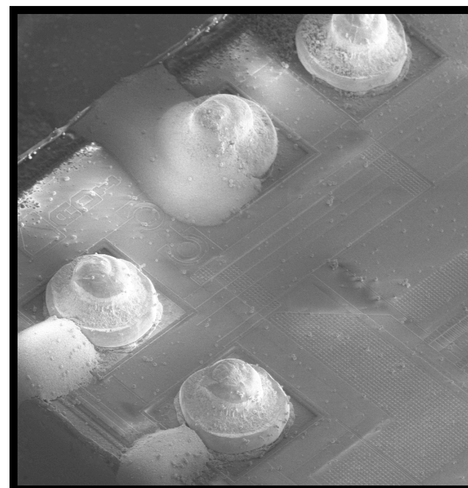


Fig. 3 – Scanning Electron Microscope Photo Showing 3D Printing of Silver Trace Over Remaining Exposed Aluminum Pad.

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II. Gold Aluminum Reliability (Kirkendall Voiding and Horsting Voiding)

The Kirkendall effect arises when two distinct materials are placed next to each other and diffusion is allowed to take place between them. In general, the diffusion coefficients of the two materials in each other are not the same. This is only possible if diffusion occurs by a vacancy mechanism; with an exchange mechanism, atoms will cross the interface in pairs, so the diffusion rates will be identical. The material with the higher diffusion coefficient will have a larger associated vacancy flux into it, so the net movement of vacancies will be from the material with the lower diffusion coefficient into the material with the higher diffusion coefficient.[4]

The Au/Al interface is commonly known to be susceptible to Kirkendall voiding for temperatures greater than 150C and is most notably seen in wire bonding technology. This effect increases significantly with the contribution of any impurities present. Three of the important contaminants that have this effect, known as Horsting effect (Horsting voids) are fluorine, chlorine, and bromine. Both Kirkendall and Horsting voids are known causes of wire bond fractures, though historically this cause is often confused with the purple colored appearance of one of the five different gold-aluminum intermetallic compounds commonly referred to as "purple plague" and less often "white plague".[5]

Thus, gold wire bonds on aluminum bond pads commonly form brittle and non-conductive intermetallic compounds at higher temperatures. The main focus of this paper is to document how the reliability and resistivity of a 3D printed aerosol silver overspray reacts to high temperature exposure over time.

III. Additive Manufacturing Assembly With 3D Silver Aerosol Printing

Silver was the element chosen for this study due to its relative low resistivity, ability to be deposited easily in an aerosol, and generally lower susceptibility to Kirkendall voiding in an Ag-Al system relative to a gold/aluminum interface. The Ag-Al phase diagram is very complex, with many intermetallic phases. Kirkendall voids can occur in this metal system as well, but typically at temperatures much higher than the operating range of the microcircuits. In practice, Ag-Al bonds can degrade due to inter-diffusion and oxidize in the presence of humidity. Chlorine is the main driving element of the corrosion process. Care was taken in this study to maintain extremely low levels of both humidity and halides within the assembly process.

Figure 4 below depicts the test vehicle used in this study as seen in its conventional bonding assembly (i.e., gold wire bonds).

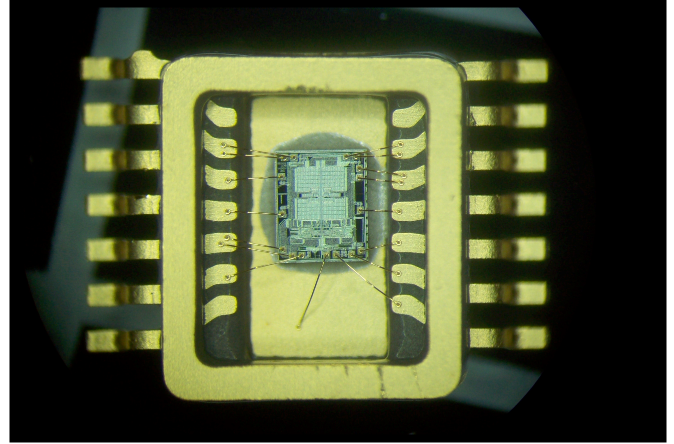

Fig. 4 – Test Vehicle with Conventional Gold Wire Bonds.

Figure 5 illustrates how the 3D printer was programmed to emulate the bonding structure seen in Figure 4.

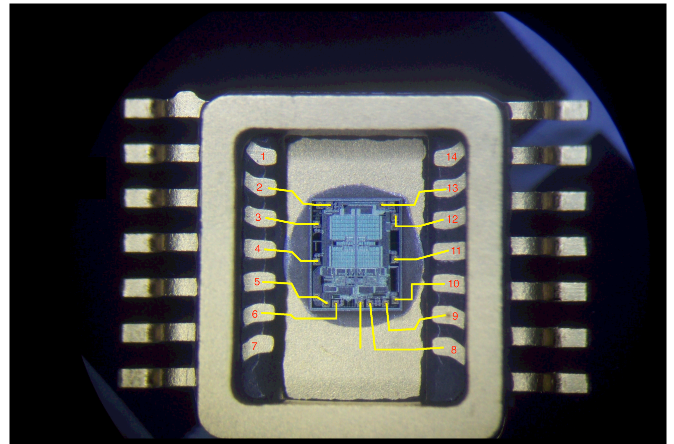

Fig. 5 – 3D Bond Layout as Programmed to Emulate the Bond Wire Connections seen in figure above.

Additional programming was performed to not only develop a pad overspray area acceptable for sufficiently low resistivity connections to the die, but also to maintain proper isolation between the individual die pads in order to prevent inadvertent shorting. Figure 6 depicts the pattern programmed.

Lastly, prior to being able to print the connections, the steep sidewalls associated with both the die and the package bond post had to be filled with material to generate a slope conducive to maintaining connectivity following aerosol deposition and curing (see Figure 7).

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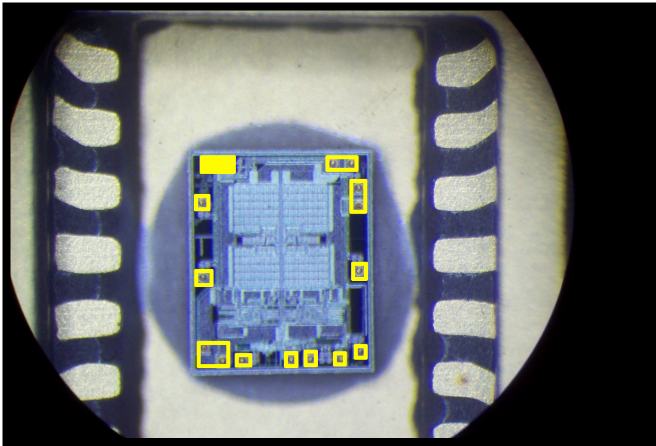

Fig. 6 – 3D Die Overspray Target for Each Required Die Pad.

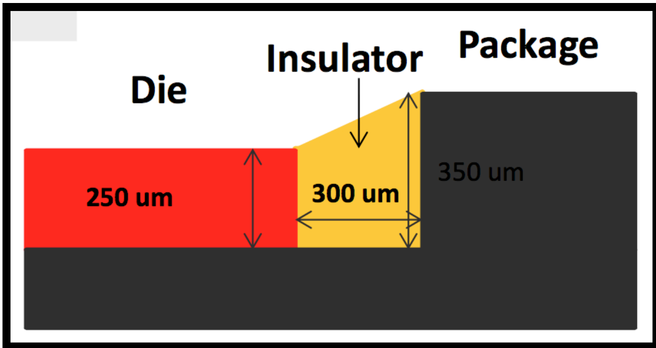

Fig. 7 – Illustration of Required Insulator Deposition for Subsequent Silver Printing.

Finally, the connections could be successfully achieved with 3D silver aerosol printing as seen below in Figure 8.

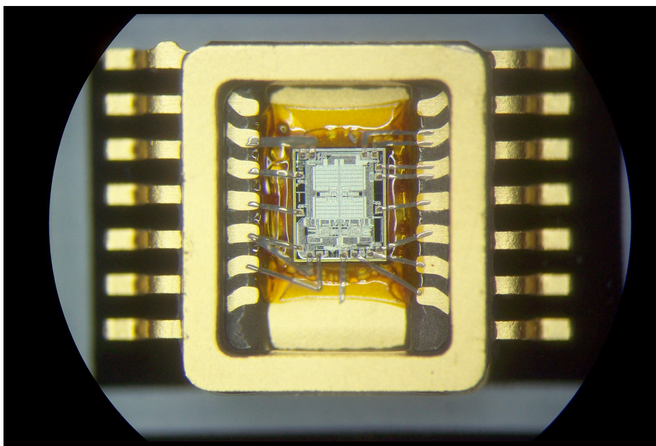

Fig. 8 – 3D Printed Connections Between Die and Package.

IV. High Temperature Reliability Of Silver/Aluminum Interface

Several devices were produced identically with this process and hermetically sealed. Resistivity measurements were taken at weekly read points (incremental 168 hour test points) to determine the point of failure relative to the original plastic component and also compared to additional, identical die that were extracted and reassembled with other high-temperature connectivity processing. The involved bake was unbiased at 250C.

Figure 9 below best summarizes the data taken to date, where it can clearly be seen that there are still no failures with this packaging option through 1100+ hours of 250C testing.

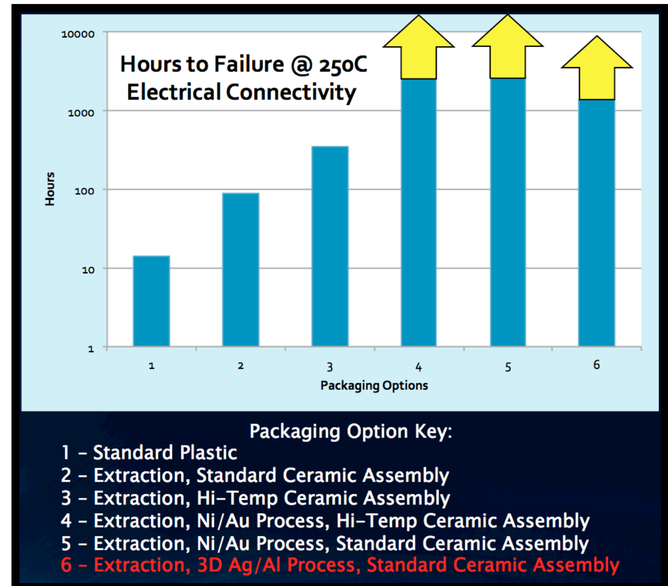

Fig. 9 – 250C Unbiased Bake Data Showing Electrical Connectivity vs. Time for Six Packaging Options Using Identical Die.

Typically, bond pull data is also taken to track pull strengths over time and temperature exposure as well. In this particular study, bond pull data was obviously not relevant. The study is scheduled to be completed at 3500 hours, or upon connectivity failure, whichever occurs first.

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V. Conclusion

High-Temperature connectivity reliability for semi-conductor components has always been a concern for any die manufactured with gold wire bonding on aluminum die pads. Kirkendall and Horsting voiding related failure mechanisms become much more significant with exposure to temperatures above 150C for these processes. With the increasing capability of 3D printing (additive manufacturing), it has now become possible for semiconductor die to be ‘wire bonded’ through alternative means. One of the benefits to performing die connections with additive manufacturing is the ability to choose materials that can optimize performance and reliability. In this study, silver was chosen to accomplish both.

Perhaps the single most significant benefit achieved with additive manufacturing for die assembly connectivity is that gold ball removal and aluminum pad ENEPIG (Electroless Nickel, Electroless Palladium, Immersion Gold) plating is not required to produce high-temperature reliability devices for extracted die using conventional packaging assembly. As is well known in the high-temperature semiconductor community, extracted die from commercial plastic are routinely used to create low to medium volume ceramic/hermetic solutions for downhole and other rugged applications.

Acknowledgment

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References

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[3] Ibid., Increased High-Temperature Reliability and Package Hardening of Commercial Integrated Circuits (Through Die Extraction, Electroless Nickel/Gold Pad Reconditioning, and Ceramic Re-Assembly).

[4] IVF, The Swedish Institute of Production Engineering Research and The Nordic Electronics Packaging Guide

[5] Gold and Aluminum-Wire Bonding Designed for High-Temperature Applications", Atotech Deutschland GmbH, Berlin, Germany Atotech USA Inc., Rock Hill, SC, USA

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